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Engineering Parameters Related to Rollover Frequency

Ian S. Jones
Forensic Technologies International
Maria B. Penny
Resource Planning Corp.

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ABSTRACT

Rollover frequency in single vehicle crashes is much higher for pickup trucks and utility vehicles (60-80 percent) than it is for cars (30-50 percent). Vehicle parameters affecting stability (and thus rollover) were examined to determine their contribution to the difference in rollover frequency among passenger cars, pickup trucks and utility vehicles. Logistic regression techniques were used to develop parameter estimates for the risk of rollover in single vehicle fatal crashes. Fatal Accident Reporting System (FARS) data for 1981-1987 were used together with engineering data for 11 models of pickup, 16 models of utility vehicle and 11 models of passenger car. Separate parameter estimates were derived for the three vehicle types to predict risk of rollover in rural and urban areas. Among vehicle design parameters, track width to center of gravity height was the strongest predictor of vehicle rollover for pickup trucks and utility vehicles; for utility vehicles, wheelbase to track ratio was also significant. For passenger cars, wheelbase was the best predictor of rollover risk. A combined model was run to establish whether a single model could be used to predict rollover risk for all three vehicle types. Wheelbase, track width to center of gravity height and driver age were all significant predictors of rollover risk, but were not sufficient to explain all the variation in rollover risk between light trucks and passenger cars. The models showed that reducing the track width to center of gravity height ratio of trucks to that for passenger cars could reduce rollover frequency by as much as 60 percent.

INTRODUCTION

The number of light trucks including vans, pickups, and utility vehicles has increased substantially over the past five years, and light trucks now constitute almost one-third of the new vehicle market.[1] As a consequence of the increased numbers of these vehicles, which are designed differently than passenger cars and are not subject to the same safety performance standards, there has been concern that this group of vehicles is over-involved in crashes.[2] Earlier studies have shown that light trucks have a propensity to roll over. [3,4] However, it is not clear to what extent this is inherent in the type of vehicle (i.e., light trucks are designed for high ground clearance and/or load carrying capacity and thus have a higher center of gravity than passenger cars), or whether it occurs because these vehicles are operated under different conditions.

A recent study provided comparisons of occupant fatality rates for various size categories of late model passenger cars and light trucks. Involvement rates were computed using data from the Fatal Accident Reporting System (FARS) and the R.L. Polk and Co. vehicle registration data.[2] Occupant fatality rates decreased with increasing size of car and with increasing size of light truck (Figure 1), although the rates for light trucks were generally higher than for passenger cars. Light truck fatality rates in multiple-vehicle crashes were similar to those of comparably sized passenger cars, whereas the single-vehicle fatality rates for light trucks were about double those for comparably sized passenger cars (except for small utility vehicles which were over four times the rate for small passenger cars).

The fatality rates for single-vehicle rollover crashes mirror those for single-vehicle crashes suggesting that the fatality rate is dominated by rollover crashes. Moreover, light trucks have a much higher proportion of rollover crashes involving *fatalities* (60-80 percent) than do passenger cars (30-50 percent), and this to a large extent accounts for their higher single-vehicle fatality rate.

Because of the wide variation in rollover frequency that clearly exists between vehicle types, this paper examines whether vehicle design factors affecting stability are correlated with rollover frequency in fatal crashes. In particular, the issue of whether differences in stability characteristics account for the difference in rollover rates between pickup trucks, utility vehicles and passenger cars is examined.

METHODS AND MATERIALS

Engineering Analysis

To assess the relative importance of vehicle design versus operating characteristics, appropriate *vehicle* stability characteristics must be defined in terms of engineering variables. There are two common mechanisms of rollover: overturning by sliding and overturning by tripping.

For a vehicle to roll over by sliding (Figure 2a), the lateral acceleration a_y is given by the expression:

$a_y > T/2h_{cg}$;
where T = track width of vehicle
h_{cg} = center of gravity height of vehicle

Once the lateral acceleration exceeds the value of this ratio, the vehicle will rollover. This means that in a cornering maneuver the larger the value of the ratio track width to center of gravity height (cg height), the less likely the vehicle is to rollover than slide out. Accordingly, the frequency of rollover should correlate with this ratio for specific makes and models of vehicles. That is, models that have low values of the ratio half track width to cg height should have a higher rollover frequency. Earlier research established that such a correlation exists for passenger cars and also explored other variables that describe propensity to rollover in tripping situations.[5,6]

Rollover by tripping (Figure 2b) can be caused by the vehicle striking a curb or from the wheels digging in after sliding onto soft ground. The lateral velocity required to roll over from a tripping situation was shown to be:[5,6]

$$v^2 \geq \frac{2g\,I_o}{m\,h_{cg}}\sqrt{1+\left(\frac{y}{h_{cg}}\right)^2}-1$$

Where I_o is the roll moment of inertia about the contact point, h_{cg} the center of gravity height, y the half the track width, and m the vehicle mass. Approximating the roll inertia as $I_o = M(w^2 + H^2)/12$ where w is the width of the vehicle and H the height and assuming $w = 2y$ and $H = 2h$ the expression for the lateral velocity for tripping can be simplified to:[7]

$$v^2 \geq \frac{8}{3}gh\left(1+\frac{y^2}{h^2}\right)\left(\sqrt{1+\frac{y^2}{h^2}}-1\right)$$

This expression suggests that candidate variables to describe propensity to *rollover* in a tripping situation include center of gravity height and the track width to cg height ratio.

In addition to those parameters that describe rollover propensity directly, other variables which describe *directional* stability should also be considered. For example, if rollover is related to the magnitude of the lateral acceleration, the vehicle's wheelbase to track width ratio could also be important because this gives an *indication* of how quickly the yaw velocity (and hence lateral acceleration) can build up.

Values for the variables, wheelbase, track width and center gravity height were obtained for as many models of passenger cars and light trucks as possible.[3,4,8-11] The values for the makes/models of vehicles analyzed in this paper are given in Table A1.

Statistical Analysis

Single vehicle crashes involving pickup trucks, utility vehicles and passenger cars were obtained from the Fatal Accident Reporting System (FARS)[12] and matched with engineering data, from Table A1, for each individual make and model of vehicle. Although the engineering data were taken from a specific model year vehicle, all applicable model years for that vehicle were included. A total of 11 models of pickup truck, 16 models of utility vehicle and 11 models of passenger car were covered. The data from the accident file and the engineering variables were used to estimate the odds of a rollover, given a single vehicle crash, as a function of the engineering parameters: wheelbase, track width to cg height ratio, and wheelbase to track width ratio. The estimates are derived through multiple logistic regression techniques that control for the simultaneous effects of driver age.[13] Separate results were obtained for rural and urban areas. This analysis covers accidents occurring during the years 1981-1987. Only single vehicle crashes were considered because rollover is predominantly a single vehicle crash problem and mechanisms of rollover in multi vehicle collisions are likely to be different. Table 1 summarizes the sample size available for each vehicle type.

To fit the regression models, the logistic regression procedure (Proc Logist) *from the SAS* Users Group International (SUGI) supplemental library of the SAS Institute was used.[14] The dependent variable in each observation is the presence or absence of rollover in a single vehicle crash involving a fatality. This variable was assigned a value of one if the vehicle rolled and zero otherwise.

The regression equations were used to predict the log odds of rollover in a single vehicle fatal crash. The log odds are the log of the ratio of two probabilities. The numerator is the probability that the vehicle will rollover; the denominator is the probability that this will not occur. These odds are predicted as a function of *driver* age as well as wheelbase, ratio of track width to center of gravity height and track width wheelbase ratio for the particular make and model of vehicle involved in the accident. Because there is no a priori way to establish whether the engineering variables account for all the variation between vehicle types and because their rollover mechanisms may be different, separate analyses were run for passenger cars, pickup trucks and utility vehicles. Separate analyses were also run for urban and rural areas because the mechanism of rollover could be different in these areas. To develop a single model to predict rollover odds, a model was fitted with all vehicle types combined by including a categorical variable defining vehicle type. Where appropriate, the predictor variables were centered about their mean value.

To illustrate the relationships between the independent variables, the correlation matrices for rural and urban areas are given in Table 2. Note that a categorical variable vehicle type is included which takes the value 0 for passenger cars and 1 for pickup or utility vehicles. In rural areas, the strongest correlation occurs between vehicle type and the track width to cg height ratio (cars have high values of track width to cg height ratio, trucks have low values). With the exception of the parameter combinations (track to wheelbase) and (track to cg height) and (track to wheelbase) and (driver age), all other parameter combinations show some correlation (this is due in part to the large sample size). The pattern for urban areas is similar.

RESULTS

Parameter estimates for rural areas given in Table 3, were derived using the forward stepwise option *of Proc* Logist. Separate estimates were derived for pickup trucks, utility vehicles and passenger cars. Independent variables for possible inclusion were: driver age, wheelbase, track width to cg height ratio and track width to wheelbase ratio.

For pickup trucks, the estimates are based on 3363 observations with 1873 rollovers; driver age and track width to cg height ratio were the best predictors of rollover odds. The remaining variables did not reach the 5 percent significance required for inclusion. Thus, once the variables driver age and track width to cg height ratio are included, neither wheelbase nor track width to wheelbase ratio are important predictors of rollover odds. Both driver age and track width to cg height parameter estimates have a negative sign, indicating that rollover odds decrease with increasing driver age and increasing track width to cg height ratio.

For utility vehicles, there were 1224 observations with 720 rollovers. Track width to eelbase ratio and track width to cg height ratio were the best predictors. The track width to wheelbase ratio has a positive sign indicating that rollover increases as this ratio increases or vehicles that are short in length relative to their width have higher rollover odds. The track width to cg height ratio has negative sign which is consistent with the pickup truck model.

For passenger cars, the estimates were based on 5153 observations with 1882 rollovers. Wheelbase and driver age were the best predictors of rollover odds, and track width to cg height did not enter the model. Both parameter estimates have negative sign indicating that larger (or longer wheelbase) cars and older drivers have lower rollover odds. At first sight the passenger car model is quite different from the pickup and utility vehicle models. However, although wheelbase is selected in preference to the track width to cg height ratio, the two parameters are correlated, and, as Table A1 shows, center of gravity heights do not vary substantially across passenger car models such that the track width to cg height ratio becomes a surrogate for vehicle size.

To illustrate the goodness-of-fit of the kup truck/utility vehicle models, Figure 3 shows for rural areas, the expected probability of rollover plotted against observed probability. Note that the passenger car model has not been included. Expected probabilities for each model of vehicle are computed by multiplying the parameter estimates by their mean values (calculated from the observations for that vehicle). Quite clearly there is good correspondence between expected and observed probabilities which is reflected in the fraction of concordant pairs between predicted and observed responses; 0.61 for pickup trucks and 0.58 for utility vehicles shown in Table 3.

To illustrate the influence of the track width to cg height ratio on rollover odds, Figure 4 shows expected probability of rollover in rural areas plotted against this ratio. The expected probability for each make/model was generated by setting the other parameters at their mean values for that model. The figure shows a monotonically decreasing risk of rollover with increasing track width to cg height ratio. The rollover risk decreases from 0.8 to 0.5 (a decrease of 38%) from a corresponding increase the track width to cg height ratio of 1.0 to 1.3. r a vehicle with a nominal track width of 60 inches this would represent a decrease in cg height of 7 inches. **Also evident from the figure is** that the effect of the track width to cg height ratio is more pronounced for the utility vehicles than the pickup trucks, a fact that is reflected in the magnitude of their parameter estimates (i.e.-2.45 for pickups compared to -7.40 for utility vehicles).

Table 4 gives the parameter estimates derived to predict rollover odds in urban areas. The estimates are based on 1343 observations with 345 rollovers for pickup trucks; 534 observations with 278 rollovers for utility vehicles and 4219 observations with 529 rollovers for passenger cars. The variables selected for the pickup truck model and the passenger car model are the same as *for rural* areas; however, in the utility vehicle model, wheelbase is selected in preference to the track to wheelbase ratio. Table 2 shows that both of these variables are strongly correlated. Thus, the models for rural and urban are very similar.

Because the models for pickup trucks and utility vehicles are quite similar, it could be argued that they *should be* treated as one vehicle type. Also, in trying to understand the relationship between rollover odds and the track width to cg height ratio, it could be argued that passenger cars represent the high end of the range but treated as a separate group don't exhibit a wide enough range to develop a significant relationship. To explore these ideas, further parameter estimates *were derived* for the combined sample of pickup trucks, utility vehicles and passenger cars. To differentiate between vehicle types two categorical variables were used "pickup" and "utility"; "pickup" taking the value of 0 for cars or utility vehicles and 1 for pickups, and "utility" taking the value of 0 for cars or pickups and 1 for utilities. Table 5 gives the parameter estimates to predict rollover odds in rural areas and Table 6 the corresponding estimates for urban areas. The models are very similar showing that driver age, wheelbase and track width to cg height ratio are strong predictors of rollover odds. All three parameter estimates are negative indicating that rollover odds decrease with increasing driver age, increasing wheelbase (large vehicles are less likely to roll than small vehicles) and increasing track width to cg height ratio. However, both models show that, after taking account of the variation explained by these engineering parameters and the driver age parameter, there is still a significant unexplained variation between passenger cars, pickup trucks and utility vehicles. That is, for both rural and urban areas, the vehicle type parameters are significant. For rural areas the parameter estimate for pickups (0.695) is not significantly different ($p < .05$) from that for utility vehicles (0.965), but both are significantly different from zero, i.e. passenger cars. The same holds true for urban areas. Thus, in terms of predicting rollover odds there is no difference between pickup trucks and utility vehicles (once driver age and the *engineering parameters* are included), although both are significantly different from passenger cars.

To illustrate goodness-of-fit, Figure 5 shows for rural areas, expected probability of rollover plotted against observed probability. It is clear that the combined model is a good predictor of rollover for all three vehicle types. To explore the influence of the track width to cg height ratio on rollover odds for this combined model, Figure 6 shows expected probability of rollover in rural areas plotted against this ratio. The figure shows a monotonically decreasing risk of rollover with increasing track width to cg height ratio irrespective of vehicle type.

DISCUSSION

This analysis of FARS data shows that there are significant relationships between the risk of rollover in single-vehicle fatal crashes and engineering parameters that describe vehicle stability. Of the vehicle stability variables considered, track width to cg height ratio was the strongest predictor of vehicle rollover for pickup trucks and utility vehicles, although for passenger cars wheelbase was a better predictor. For utility vehicles track width to wheelbase ratio was also a strong predictor of rollover, suggesting that vehicles that are short in length relative to their width are more likely to rollover than longer wheelbase vehicles. The regression models for rural and urban areas were substantially similar indicating that the mechanisms of rollover are the same.

The separate parameter estimates for pickups, utility vehicles and passenger cars establish that pickup and utility vehicles behave in similar ways. That is, rollover odds can be predicted using track width to cg height ratio for both vehicle types. In terms of other parameters, driver age appeared more important as a predictor of rollover for pickup trucks. This is in part due to the limited range of this variabl for utility vehicles because utility models had very high proportion of young drivers. Similarl the track width to wheelbase parameter whic was a significant predictor of rollover for utili vehicles did not work for pickups. The range c this parameter for pickups is limited because, I general, all pickups have fairly long wheelbase in relation to their track width. Utility vehicle on the other hand have a much wider range wheelbase. For example, there are a number short utility vehicles (Suzuki Samurai, 2 do Montero, etc) as well as longer wheelbas vehicles (Toyota Land Cruiser, Isuzu Troope etc.) included in the sample.

This lack of range for particul parameters also explains why the track width cg height ratio was not a good predictor rollover for passenger cars. With one or tv exceptions, center of gravity heights passenger cars all fall within a small range. Th means that track width to cg height ratio becom a surrogate for track width or more genera vehicle size which is why wheelbase becomes t strongest predictor of rollover.

Trying to develop separate models for t three vehicle types clearly had problems becau of the limited ranges of some paramete Combining the vehicle types into one model using vehicle type categorical variables pickup trucks and utility vehicles established th driver age, wheelbase and track width to cg hei ratio were significant predictors of vehi rollover. However, both vehicle type paramet were significant suggesting that there was s some remaining variation attributable to vehi type. To illustrate the magnitude of the vehi type effect, if for a pickup truck the track wi to cg height ratio were increased from 1.0 (end of light trucks) to 1.5 (an average passen car), the log odds of rollover would be reduced 0.74 (-1.487 x 0.5) which is approximately same magnitude as the pickup vehicle t variable (0.695). This suggests that there some other effect contributing to light tr rollover which has a similar magnitude to track width to cg height parameter. It could argued that this still reflects different opera conditions, although, this analysis has contro for driver characteristics and to some ext environmental conditions by separating rural urban areas.

The effects of other environmental fac were explored including road curvature, r ade, weather conditions, and region of country and while some showed significant correlation none changed the basic relationship between light trucks and cars. That is, even after taking account of variation explained by these variables, the vehicle type parameter was still significant. However, although there is a residual vehicle type effect, it should be stressed that a substantial part of the difference between light trucks and cars is due to their higher center of gravity heights. This is confirmed by looking at car models that have low track width to cg height ratios. For example, Figure 6 shows that cars which have unusually low ratios have correspondingly high rollover probabilities that are in the same range as light trucks with equivalently high track width to cg height ratios.

The association between center of gravity height and increased rollover frequency for light trucks compared to passenger cars has been recognized by others.[15] Although limited to four older model utility vehicles and 11 passenger car models, this study did show that vehicles with low track width to cg height ratios had higher rollover rates than passenger cars with high ratios. What clear from this and the current study is that vehicles with high centers of gravity in relation to their track width will roll over more frequently.

The fact that rollover risk is correlated with track width to cg height ratio raises the question of whether safety performance standards should be written to control rollover propensity. The issue of whether a standard could be established using a stability factor criterion based on cg height and track width has already been raised in a petition to NHTSA.[16] Such a simplified approach has limitations because, for example, it does not differentiate between small vehicles that could roll over more frequently than large vehicles (given that both have the same track width to cg height ratio). However, the results presented in Figure 6 show that adopting a lower limit of 1.25 for the track width to cg height ratio could reduce substantially the rollover frequency of light trucks. In denying this petition, NHTSA argued that this approach does not take account "of vehicle characteristics that contribute to a vehicle's becoming involved in an accident which includes rollover."[17] That is, a ehicle's handling performance may contribute to high crash rate, which in turn produces a high rollover rate not because of poor stability but poor handling performance. Previous research looked somewhat unsuccessfully for an appropriate handling performance/stability maneuver to describe overall risk to roll over.[18] This earlier work concentrated on differentiating between the rollover propensity of small and large passenger cars and the handling/stability parameter values for all the vehicles generally were well below the threshold of rollover for light trucks. However, performance maneuvers of this type should be reviewed to establish whether they could be used to differentiate between passenger cars and light trucks and whether they would identify vehicle designs that have an unacceptably high risk of rollover.

ACKNOWLEDGMENT

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TABLE 1 --Single Vehicle Crash Sample Size - FARS 1979-1987

	Rural		Urban	
Vehicle Type	N	% Rollover	N	% Rollover
Pickup	3363	56	1343	26
Utility	1224	75	534	52
Car	5153	37	4219	13

TABLE 2--Correlation Matrix of Independent Variables

URBAN AREAS (N = 8740)

	WHEELBASE	TRACK/ WHEELBASE	VEHICLE TYPE	TRACK/ CG HEIGHT	DRIVER AGE
Wheelbase	1.0	-0.30	0.187	0.24	0.21
Track/Wheelbase		1.0	0.31	-0.12	-0.06
Vehicle Type			1.0	-0.71	-0.16
Track/Cg Height				1.0	0.22
Driver Age					1.0

RURAL AREAS (N = 6096)

	WHEELBASE	TRACK/ WHEELBASE	VEHICLE TYPE	TRACK/ CG HEIGHT	DRIVER AGE
Wheelbase	1.0	-0.33	0.25	0.26	0.14
Track/Wheelbase		1.0	0.25	-0.03	-0.05
Vehicle Type			1.0	-0.61	-0.15
Track/Cg Height				1.0	0.18
Driver Age					1.0

TABLE 3--Regression Equation for Rollover Odds in Single Vehicle Crashes in Rural Areas by Type of Vehicle

For Pickup Trucks

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	0.236	0.035	44.48	<.0001
Driver Age	-0.018	0.002	55.04	<.0001
Track/cg Height	-2.453	0.340	52.12	<.0001

Model Chi-square = 125.61 with 2 D.F.
Fraction of concordant pairs = 0.611
N = 3363 (rollovers = 1873)

For Utility Vehicles

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	1.142	0.068	280.43	<.0001
Track/Wheelbase	7.767	1.982	15.35	<.0001
Track/cg Height	-7.399	1.670	19.62	<.0001

Model Chi-square = 28.72 with 2 D.F.
Fraction of concordant pairs = 0.583
N = 1224 (rollovers = 920)

For Automobiles

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	-0.578	0.030	377.76	<.0001
Wheelbase	-0.043	0.005	91.62	<.0001
Driver Age	-0.013	0.002	61.41	<.0001

Model Chi-square - 198.21 with 2 D.F.
Fraction of concordant pairs = 0.620
N = 5153 (rollovers = 1882)

TABLE 4--Regression Equation for Rollover Odds in Single Vehicle Crashes in Urban Areas by Type of Vehicle

Pickup Trucks

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	-1.149	0.067	290.90	<.0001
Track/cg Height	-4.156	0.607	46.76	<.0001
Driver Age	-0.024	0.005	20.19	<.0001

Model Chi-square = 82.00 with 2 D.F.
Fraction of concordant pairs = 0.662
N = 1343 (rollovers = 345)

Utility Vehicles

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	0.070	0.092	0.59	.44
Track/cg Height	-11.238	2.538	19.61	<.0001
Wheelbase	-0.041	0.013	9.27	<.002

Model Chi-square = 52.76 with 2 D.F.
Fraction of concordant pairs = 0.686
N = 534 (rollovers = 278)

Passenger Cars

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	-2.017	0.050	1646.81	<.0001
Wheelbase	-0.041	0.007	33.08	<.0001
Driver Age	-0.016	0.003	28.68	<.0001

Model Chi-square = 82.53 with 2 D.F.
Fraction of concordant pairs = 0.623
N = 4219 (rollovers = 529)

TABLE 5--Regression Equation for Rollover Odds in Single Vehicle Crashes in Rural Areas (All Vehicle Types Combined)

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	-0.441	0.054	67.55	<.0001
Wheelbase	-0.018	0.004	21.46	<.0001
Track/Wheelbase	-0.113	1.106	0.01	.92
Track/cg Height	-1.487	0.396	14.07	.0002
Driver Age	-0.015	0.001	125.83	<.0001
Pickup	0.695	0.098	50.38	<.0001
Utility	0.965	0.153	39.57	<.0001

Model Chi-square = 1000.49 with 6 D.F.

Fraction of concordant pairs = 0.684

N = 9740 (rollovers = 4675)

TABLE 5--Regression Equation for Rollover Odds in Single Vehicle Crashes in Rural Areas (All Vehicle Types Combined)

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	-0.441	0.054	67.55	<.0001
Wheelbase	-0.018	0.004	21.46	<.0001
Track/Wheelbase	-0.113	1.106	0.01	.92
Track/cg Height	-1.487	0.396	14.07	.0002
Driver Age	-0.015	0.001	125.83	<.0001
Pickup	0.695	0.098	50.38	<.0001
Utility	0.965	0.153	39.57	<.0001

Model Chi-square = 1000.49 with 6 D.F.

Fraction of concordant pairs = 0.684

N = 9740 (rollovers = 4675)

TABLE 6--Regression Equation for Rollover Odds in Single Vehicle Crashes in Urban Areas (All Vehicle Types Considered)

Independent Variable	Beta	Std. Error	Chi-square	p Value
Intercept	-1.863	0.066	799.55	<.0001
Wheelbase	-0.024	0.006	14.64	.0001
Track/Wheelbase	1.779	1.688	1.11	.29
Track/cg Height	-2.601	0.627	17.23	<.0001
Driver Age	-0.018	0.003	52.72	<.0001
Pickup	0.643	0.162	15.74	.0001
Utility	0.813	0.225	13.01	.0003

Model Chi-square = 727.06 with 6 D.F.

Fraction of concordant pairs = 0.719

N = 6096 (rollovers = 1152)

Figure 1. All Vehicle Occupant Deaths in 1 to 3 Year Old Vehicles per Registered Vehicles by Crash Type, FARS Data 1981-1985

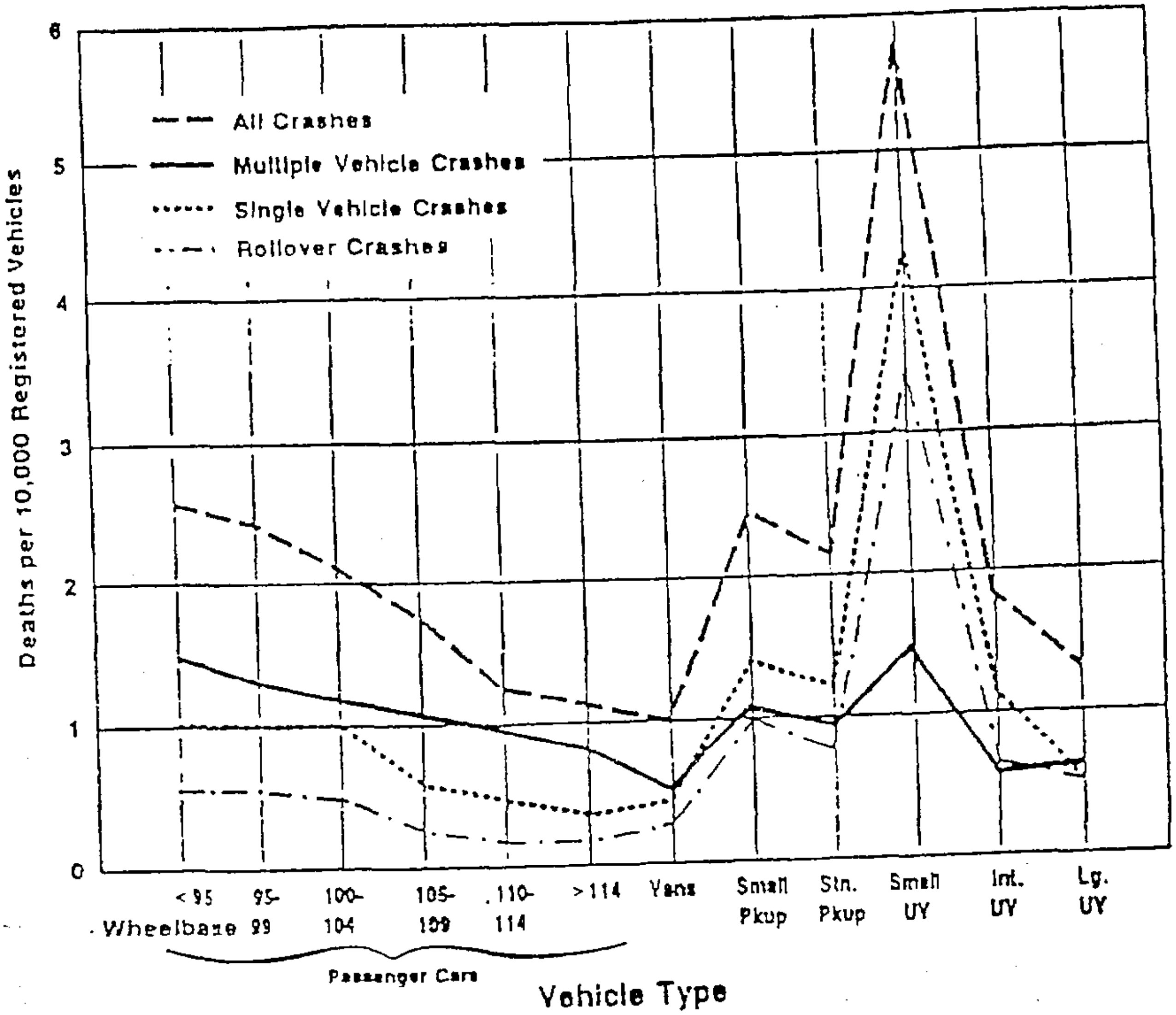
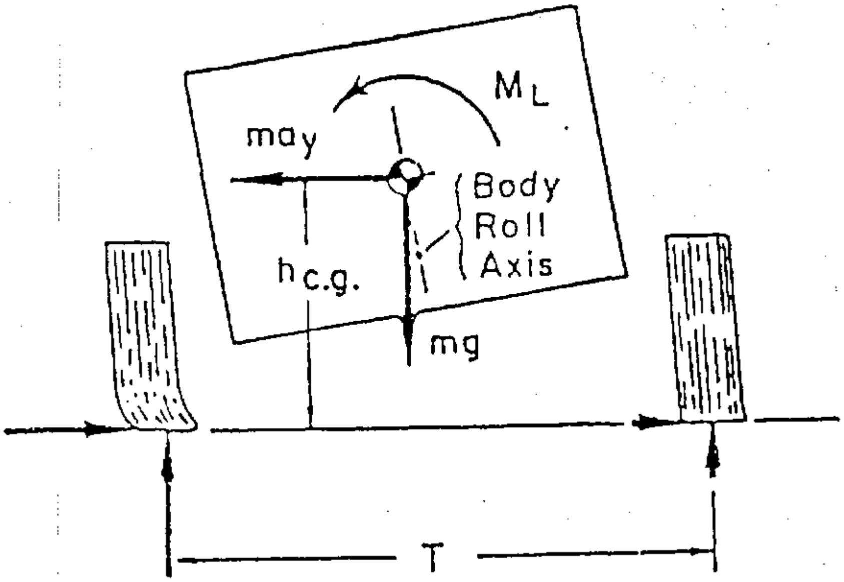
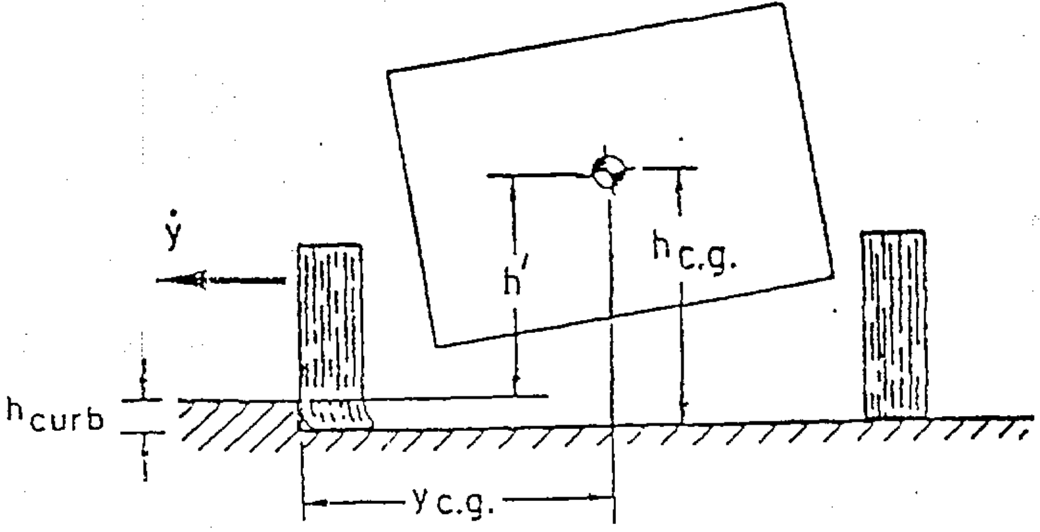


Figure 2 Common Mechanisms of Rollovers



(a) - Maneuver Induced Rollover



(b) - Tripped Rollover

Figu. ;

Expected Probability vs Observed Probability of
Rollover in Rural Areas - Separate Model

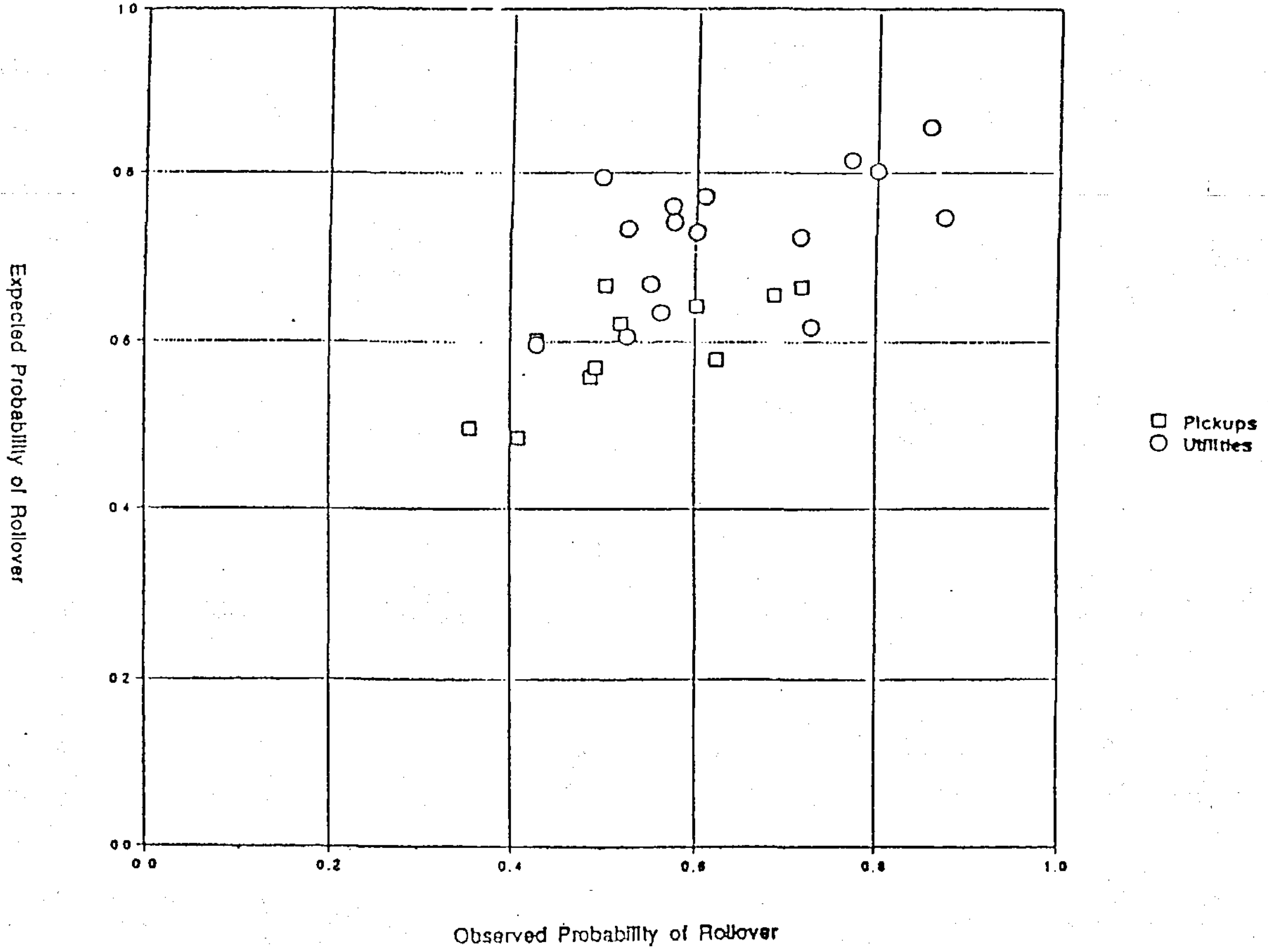
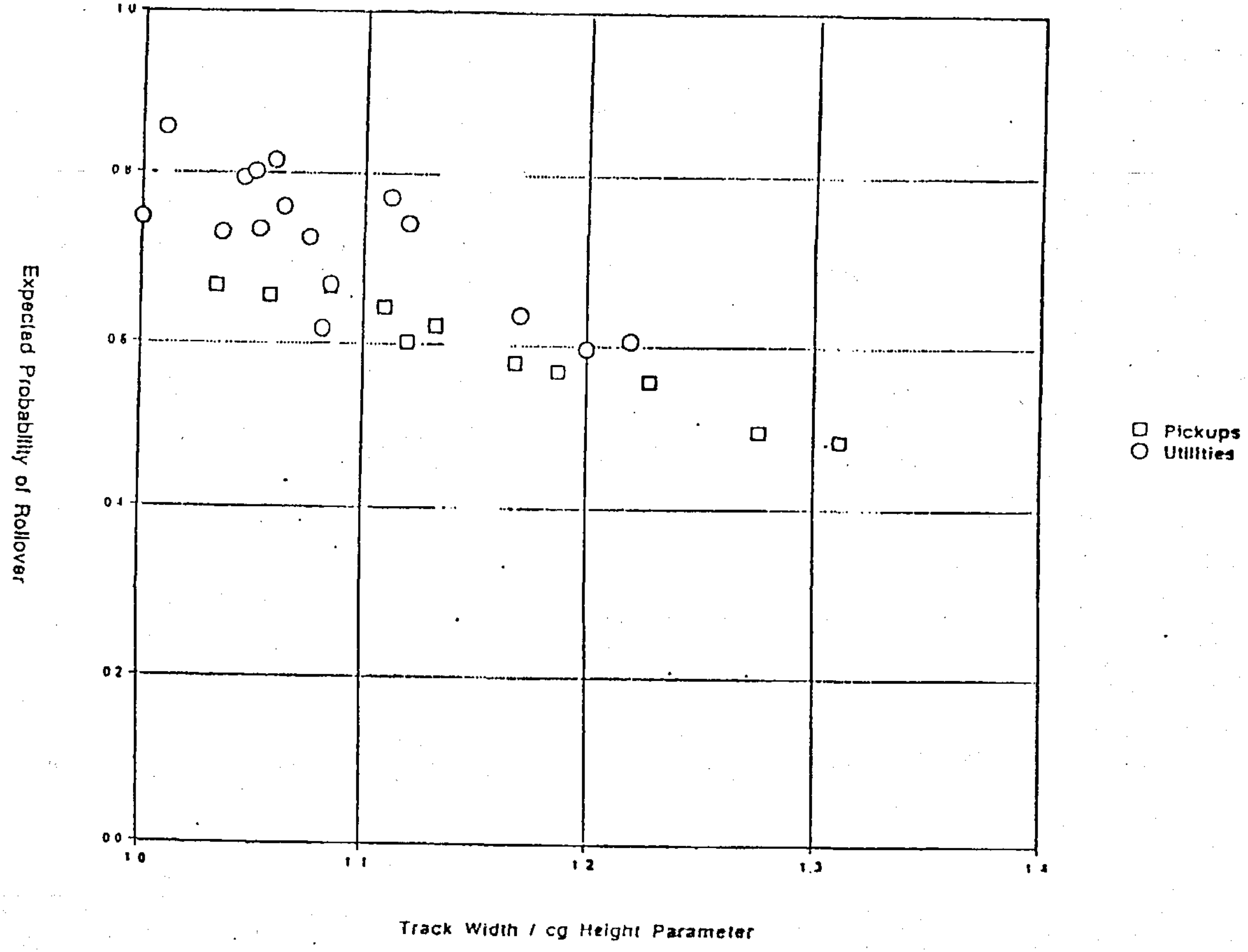


Figure 4

Expected Probability of Rollover in Rural Areas vs Track/cg Height

Separate Model



Figure

Expected Probability vs Observed Probability of Rollover in Rural Areas - Combined Model

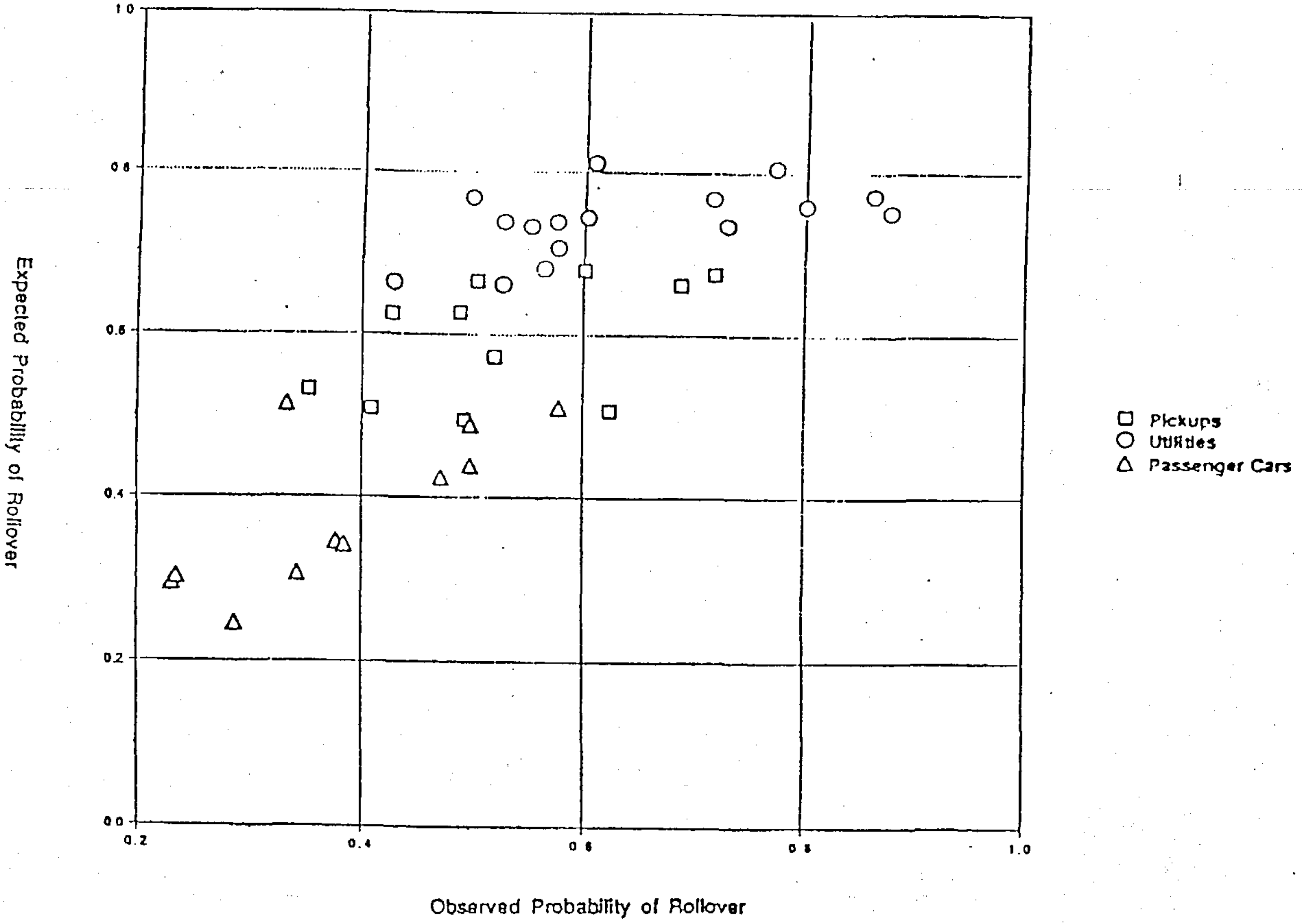


Figure 6

Expected Probability of Rollover in Rural Areas vs Track/cg Height

Combined Model

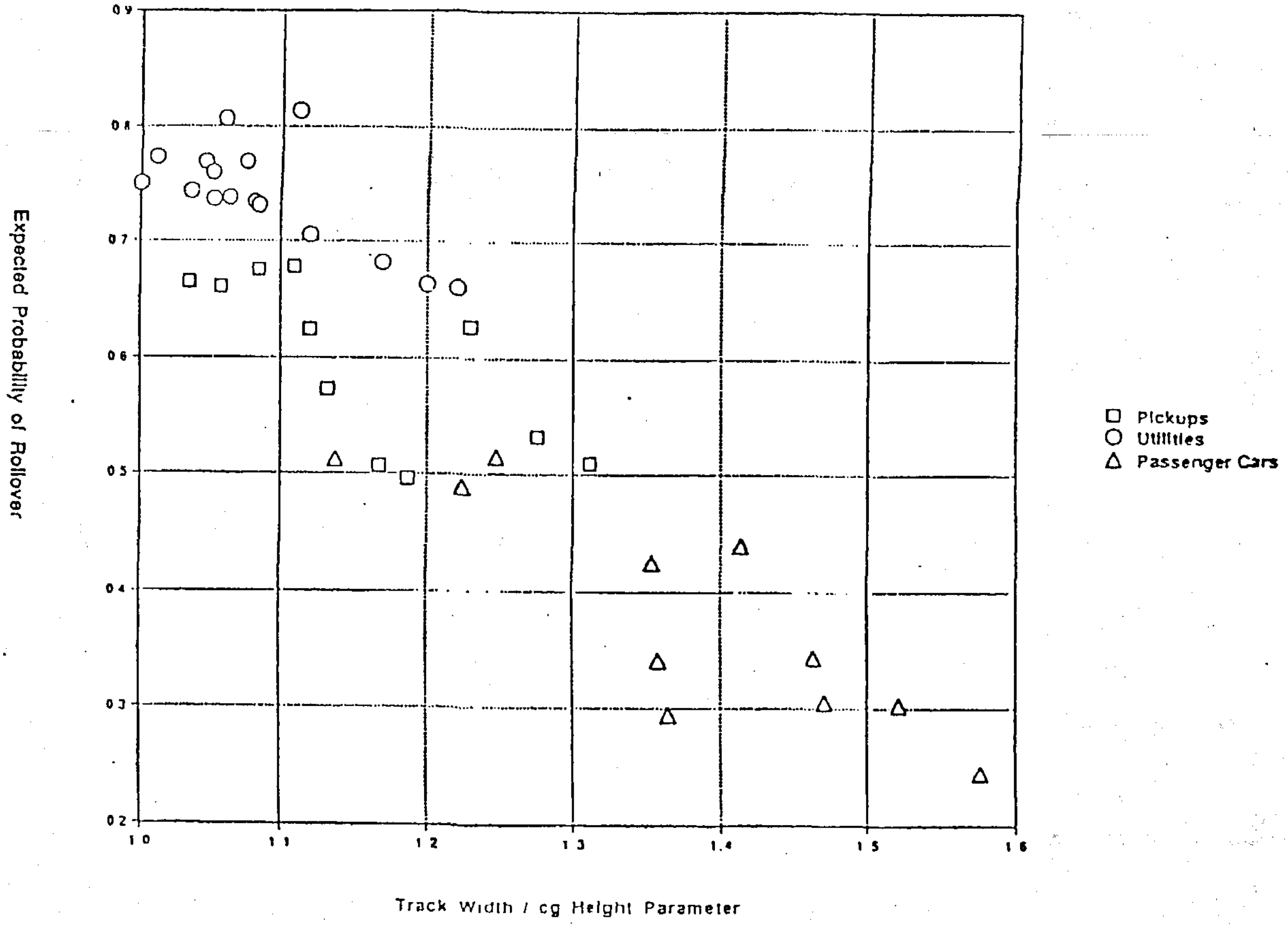


TABLE A1 -- Height of Canter of Gravity, Track Width and Wheelbase Data for Various Pickups,

Year/Make/Model	cg Height (Inches)	Track Width (Inches)	Track/cg Height	Wheelbase (Inches)	Mean Driver Age
1979 Ford F150 4x2	26.09	66.3	1.275	132.0	32.5
1982 Chevrolet C10 4x2	24.6	64.6	1.312	118.0	33.5
1982 Chevrolet S10 4x2	25.0	56.0	1.12	108.0	33.5
1986 Ford F250 4x4	27.6	65.6	1.187	133.0	31.7
1979 Toyota 4x2	21.6	53.1	1.229	102.0	29.0
1986 Toyota 4x4	25.85	56.1	1.085	102.0	24.2
1986 Chevrolet S10 4x4	24.7	55.9	1.132	108.3	27.7
1985 Ford Ranger XL	27.0	55.8	1.034	108.1	30.1
1985 Nissan 4x4	24.77	55.0	1.11	101.4	25.6
1983 Chevrolet 4x4	25.3	59.1	1.168	131.5	32.3
1987 Ford Ranger 4x4	26.5	56.0	1.057	108.1	29.3

TABLE A1 — Height of Center of Gravity, Track Width and Wheelbase Data for Various Utility Vehicles

Year/Make/Model	cg Height (inches)	Track Width (inches)	Track/cg Height	Wheelbase (inches)	Mean Driver Age
1982 Jeep CJ7	24.8	53.3	1.075	93.4	27.5
1979-83 Jeep CJ5	24.6	52.1	1.059	83.5	25.6
1986 Ford Bronco II 4x2	27.1	56.9	1.05	94.25	32.0
1983 Ford Bronco II 4x4	28.79	58.22	1.011	94.25	30.8
1983 Mitsubishi Montero	26.22	54.8	1.045	92.5	31.0
1981 Toyota Landcruiser	27.7	55.4	1.00	107.5	23.7
1982 Chev Blazer C10 4x2	27.2	65.3	1.20	106.5	33.93
1977 Jeep Cherokee	26.6	64.9	1.22	101.4	30.06
1977 International Scout	27.51	58.5	1.063	100.00	31.43
1979 Dodge Ramcharger	27.67	64.75	1.170	106.00	32.2
1983 Chevrolet Blazer S10	26.1	54.1	1.036	101.00	31.2
1987 Toyota 4 Runner	27.2	57.25	1.052	103.0	29.0
1985 Suzuki Samurai 4x4	23.02	51.2	1.112	80.0	21.8
1981 Ford Bronco	29.3	65.87	1.12	105.0	30.6
1986 Isuzu Trooper	24.96	54.0	1.082	104.5	33.8
1983 Chevrolet S10 Blazer	25.3	54.9	1.085	100.5	30.5

TABLE A1 – Height of Center of Gravity, Track Width and Wheelbase Data for Various Passenger Cars

Year/Make/Model	cg Height (Inches)	Track Width (Inches)	Track/cg Height	Wheelbase (Inches)	Mean Driver Age
1080 AMC Concord	21.1	57.3	1.358	108.0	41.1
1983 Chevrolet Caprice	22.45	61.3	1.365	116.0	44.8
1982 Chevrolet Celebrity	19.1	58.1	1.521	104.7	40.4
1979 Chevrolet Chevette	18.9	51.2	1.354	97.3	30.7
1980 Chrysler Cordoba	19.0	59.9	1.576	112.7	44.6
1978 Toyota Corolla	18.0	50.9	1.414	93.3	25.6
1981 Renault LeCar	21.8	49.6	1.138	95.2	31.2
1978 Honda Civic	20.38	50.8	1.246	86.6	30.1
1986 Chevrolet Spectrum	22.27	54.5	1.224	94.5	29.5
1985 Oldsmobile Cierra	19.64	57.8	1.471	105.0	44.1
1985 Ford Thunderbird	19.96	58.4	1.463	104.25	34.2